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A high deuterium abundance in the early Universe

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The amount of deuterium relative to hydrogen (D/H) in clouds with close to primordial abundance seen at high redshift in the spectra of distant quasars currently provides the best estimate of the baryonic density of the Universe ($\Omega_{\rm B}$). The first measurements have yielded discrepant values of D/H both high[1–5] ($\sim 2 \times 10^{-4}$) and an order of magnitude lower.[6,7] The low values of D/H imply a high $\Omega_{\rm B}$ that is difficult to reconcile with determinations of the primordial abundances of other light elements, notably ^{4}He, and with the known number of light neutrinos.[8–10] We report an independent measurement of the neutral hydrogen (H I) column density in the cloud toward Q1937−1009 where one of the low D/H values was obtained.[6] Our measurement excludes the reported[6] value and we give a lower limit of $D/H > 4 \times 10^{-5}$ in this system, which implies $\Omega_{\rm B} < 0.016$ for a Hubble constant of 100 km s^{-1} Mpc^{-1}. This new upper limit on $\Omega_{\rm B}$ relieves the conflict with standard Big Bang nucleosynthesis.

The accuracy of the measurements of D/H in high redshift quasar absorption line clouds is heavily dependent on the neutral hydrogen column density of the absorbing cloud and different problems arise in different column density regimes. At sufficiently low column density,[1–5] absorption lines of hydrogen high in the Lyman series become unsaturated and permit an accurate determination of H, but the corresponding weakness of deuterium increases the likelihood of significant contamination by a chance coincidence of weak foreground H I absorption. Alternatively, choosing a higher column density absorber minimises such deuterium contamination but the saturation of the Lyman series increases the chance of wrongly estimating the H I column density. The two low measurements of D/H ($\sim 2.3 \times 10^{-5}$) toward Q1937−1009 (ref. 6) and Q1009+2956 (ref. 7) belong in this category.

In the latter case the total amount of neutral hydrogen is hard to estimate because even the lines high in the Lyman series are nearly opaque. For the same reason, the exact velocity

distribution of H I and D I absorption cannot be determined directly but must be plausibly modelled from the distribution of the weaker absorption of other ions and this procedure can be problematical.[11] Toward Q1937−1009, Tytler et al.[6] made the minimal assumption that the simplest two-component model that accounted for low ionization absorption was sufficient to account for H I and D I absorption. Recent investigation[11] has shown that alternative models of the absorption in this cloud that have as much as three times lower H I column density can be found, which would increase D/H to 7×10^{-5}, well outside the published[6] errors.

Regardless of its actual velocity distribution, the total H I column density associated with a cloud can be found by observing the optical depth of the corresponding redshifted Lyman continuum. The different cloud models proposed[6,11] to account for the absorption toward Q1937−1009 make different predictions for the amount of residual flux below the Lyman break and these are difficult to distinguish at the required precision with the existing[6] high resolution Keck HIRES echelle spectra. In the violet spectral region, the orders of this spectrograph are closely spaced and the necessarily short slits limit the amount of sky available for sky subtraction. We have addressed this difficulty by using long-slit, lower resolution spectroscopy to measure precisely the residual flux below the Lyman continuum break.

The measurements were obtained in 1996 August with the Low Resolution Imaging Spectrograph (LRIS) on the Keck1 10m Telescope on Mauna Kea, Hawaii and consist of a total of 45 minutes exposure at lower resolution (resolving power, $R \sim 300$) through a very wide slit ($1\farcs5$) and a higher resolution ($R \sim 1500$) exposure (40 minutes total) taken through a $0\farcs7$ slit. (Seeing was less than $0\farcs8$ for both observations.) The spectra were flux calibrated with observations of a white dwarf star taken immediately after the target observations and at nearly identical zenith angle and declination, and wavelength calibrated with observations

of a Krypton-Mercury lamp in the same configuration. The two-dimensional spectral image of the quasar (Figure 1) clearly shows a residual flux below the continuum break.

The flux-calibrated and sky-subtracted low-resolution spectrum is shown in Figure 2*a*. Both the quasar flux level and the level of the unabsorbed continuum are needed for calculating the optical depth of the Lyman continuum. For Q1937$-$1009 the quasar's emission redshift is $z = 3.805$, only slightly higher that the redshift ($z = 3.572$) of the absorbing cloud used for measuring the D/H ratio. The quasar continuum at the $z = 3.572$ Lyman limit is therefore in transition, with the fluctuating absorption from numerous blended lines of individual Lyman forest clouds becoming increasingly overlayed by the overlapping Lyman continua of the forest clouds. We have considered two ways of estimating the continuum level in the $z = 3.572$ Lyman continuum region. The first was a simple linear extrapolation of the estimated continuum at longer wavelengths which is shown as the dotted line in Figure 2*a*. However, as the figure shows, even this very conservative procedure rules out the value of $N(\mathrm{H\,I})$ reported in ref. 6. Tytler reports (private communication) that in the spectral interval $4125\,\text{Å} < \lambda < 4175\,\text{Å}$ the SNR weighted residual flux $= 0.015 \pm 0.014$. This is not in disagreement with our spectra, as Figure 2 shows that this region suffers particularly heavy absorption from the Lyα forest lines. However, the total column density adopted in ref. 6 ($N(\mathrm{H\,I}) = 8.7 \times 10^{17}\mathrm{cm}^{-2}$) would predict that the residual flux below the Lyman break $= 0.004^{+0.003}_{-0.002}$ which is shown as the dashed line and error bar, and lies well below the observed spectrum. In the wavelength region from 890 Å to 900 Å we measure an average flux of 5.4 ± 0.4 counts compared to an extrapolated average continuum level of 224 counts, where the 1 σ error is made by extracting sky regions in the same way as the quasar. This corresponds to $\tau = 3.72 \pm 0.06$ or $N(\mathrm{H\,I}) = (5.9 \pm 0.1) \times 10^{17}\mathrm{cm}^{-2}$.

However, the statistical errors are small compared with the systematic error in the continuum placement and the simple procedure used above overestimates the value of the

optical depth and hydrogen column density. To provide an improved estimate, we have modelled the expected continuum level using statistical Lyα forest data.[12,13] Such models provide a good representation of the average forest absorption and we see that they also match the Q1937−1009 forest absorption rather well (dash-dot line in Figure 2*a*). So long as there are no unrecognized strong absorption systems with redshifts slightly lower than $z = 3.572$, and the model gives an acceptable representation of the Lyα forest region, the Lyman continuum absorption required by the line absorption should predict the additional Lyman continuum absorption decrement to be applied to the quasar spectrum. In high redshift Lyman α forests, such as the one in Q 1937−1009, the weak hydrogen clouds are so numerous that they blend into a quasi-smooth continuum. But Madau et al.[13] noted that the contribution to $\tau_{\mathrm{Ly}\,\alpha}$ by optically thin absorbers with $10^{16} \leq N(\mathrm{H\,I}) \leq 10^{17}\mathrm{cm}^{-2}$ is highly uncertain. In our calculation of $\tau_{\mathrm{Ly}\,\alpha}$, we retained only the first term in their eq. 5 and reduced its coefficient by 20%. This procedure assumes that there are no high column density hydrogen clouds in Q 1937−1009 with redshifts near that of the $z = 3.572$ system. This assumption is justified both by the good match of the statistical model to Lyman α forest region of our spectra and by the finding of Tytler & Burles[14] that the column densities of the three highest column density hydrogen clouds with redshifts to the blue of the D/H absorption system have $15.06 \leq \log N_{\mathrm{H}} \leq 15.7$. As the combined absorption produced by these three systems is $\leq 10\%$ of Tytler's predicted absorption for the much stronger $z = 3.572$ D/H system it can be neglected in comparison to the uncertainties inherent in setting the appropriate level for the un-absorbed quasar continuum, and the accurate determination, with only low resolution spectra, of the $z = 3.572$ Lyman continuum absorption in the presence of strong line absorption from other redshift systems. This fit reduces the extrapolated continuum level at $890-900$ Å to 126 counts, which gives an optical depth of 3.15 ± 0.06 or $N(\mathrm{H\,I}) = (5.0 \pm 0.1) \times 10^{17}\mathrm{cm}^{-2}$.

Figure 2*b* shows a linear plot of the moderate resolution spectrum in the region near the $z = 3.572$ Lyman limit. Again the two continuum estimates are shown. Here Lyα forest lines can be seen cutting into the residual flux both above and below the break. The residual flux levels from the moderate and low resolution spectra are in satisfactory agreement when the moderate resolution data is smoothed to the low resolution. Here we obtain $\tau_{\rm cont} = 3.1$ (linear extrapolation of the quasar continuum) or $\tau_{\rm cont} = 2.4$ (Lyα forest model continuum) where we have made the measurement at the rest-frame wavelength of 890 Å in the high resolution spectrum. These optical depths translate to $3.8 \times 10^{17}{\rm cm}^{-2} < N({\rm H\ I}) < 4.9 \times 10^{17}{\rm cm}^{-2}$ for the total hydrogen column density in the $z = 3.572$ absorption system.

Based on the above analysis of the two spectra, we consider a value of $5 \times 10^{17}{\rm cm}^{-2}$ to be a reasonable maximum neutral hydrogen column density that can be associated with the measured[6] deuterium column density of $N({\rm D\ I}) = 2 \times 10^{13}{\rm cm}^{-2}$. This then gives a formal minimum for D/H of 4×10^{-5}.

However, this new determination of total H I column density cannot distinguish different H I or D I velocity components and so cannot measure the D/H ratio in any one component. Spectra with a resolution R$\geq 6 \times 10^4$ are needed to resolve the velocity structure of the low-ionization metal line clouds in order to settle the issue of the number and relative strengths of the component clouds within the $z = 3.572$ system. More precise cloud information might show that a considerable fraction of the accompanying hydrogen could be located in the red wing of the line. If so, the corresponding deuterium would be obscured by overlying hydrogen, and D/H ratios even as high as 2×10^{-4} could then be accommodated by the data. We would like to emphasise that the highly uncertain and model-dependent nature of the systematic errors involved in these measurements of deuterium makes the assignment of formal systematic errors very difficult. Since this is likely to remain the case as new

measurements accumulate, we have chosen rather to emphasise a reliable lower bound, while giving some idea through modelling of the possible uncertainty.

We would therefore recommend adopting a range of $4 \times 10^{-5} < D/H < 2.4 \times 10^{-4}$ as the most conservative current interpretation of the results of determining D/H in the high redshift quasar absorption line systems. The density parameter, $\Omega_{\rm B}$, is then constrained to be $0.005 < \Omega_{\rm B}\, h^2 < 0.016$, where the Hubble constant, $H_0 = 100\, h$ km s^{-1} Mpc^{-1}. Unlike the lower D/H value of 2.3×10^{-5}, this range is broadly consistent with measurements of ^{7}Li and ^{4}He [ref. 8] and eliminates much of the evidence that suggests[9] that there might be a crisis in the Standard Big Bang Nucleosynthesis model. It remains true that the upper end of the range is in better agreement with ^{4}He and ^{7}Li measurements whereas the lower value is easier to reconcile with models of Galactic chemical evolution tied to the locally measured value of D/H, as well as with local estimates of $\Omega_{\rm B}$. This issue will be resolved only when further measurements of D/H narrow the range.

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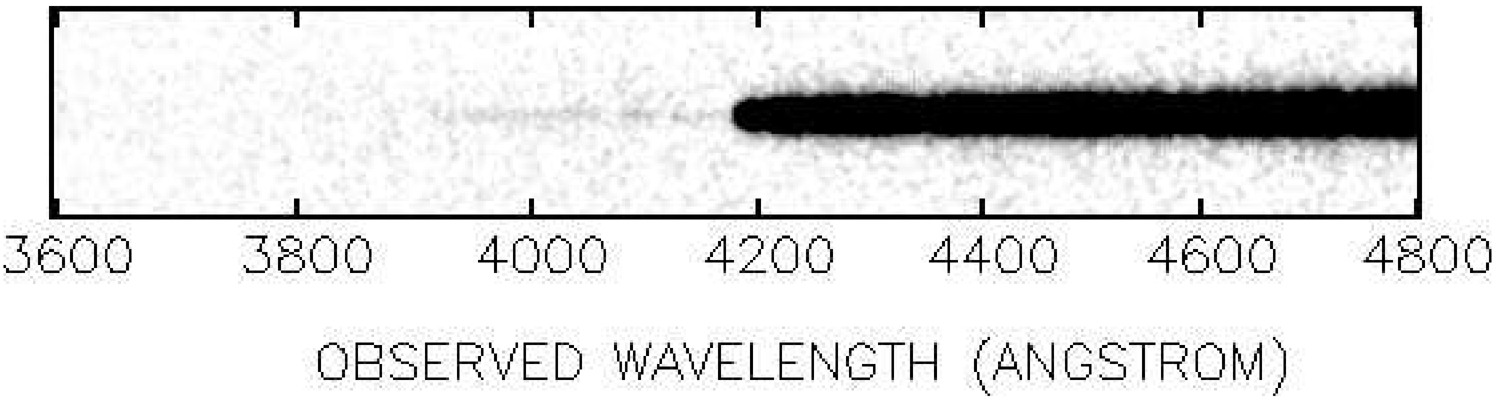
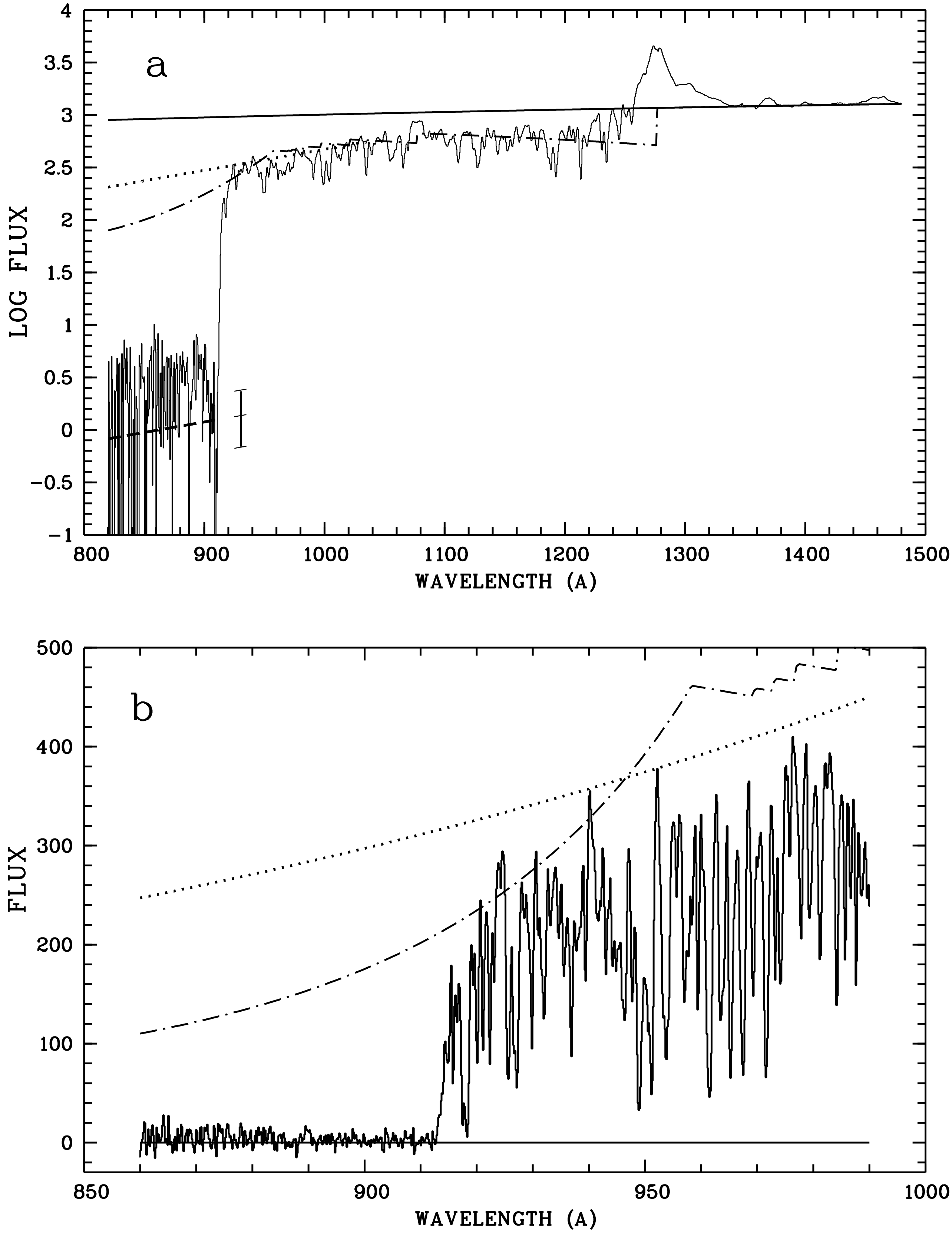


Fig. 1.— The two-dimensional spectrum of Q1937−1009 is shown in a grey-scale representation with the dispersion direction along the horizontal, covering the wavelength range from 3600 Å to 4800 Å, and the spatial direction along the vertical ($\pm 8\farcs5$ about the quasar). The Lyman continuum break is positioned at the center of the picture with the residual flux at shorter wavelengths running to the left. The spectrum was formed from 3 15-minute exposures obtained with the 300ℓ mm^{-1} grating on the LRIS spectrograph on the Keck1 10m telescope using a $1\farcs5 \times 172''$ slit. The resulting spectrum had $R = 300$. The quasar was moved to a different position along the slit between each exposure. The frames were sky-subtracted using the median of positionsrepresentation with the dispersion direction along the horizontal, covering the wavelength range from 3600 Å to 4800 Å, and the spatial from $8\farcs5$ to $4\farcs5$ from the quasar on either side of the quasar. The three frames were then median added to eliminate cosmic rays, and finally calibrated to F_ν using observations of the white dwarf photometric standard star Feige 110, obtained in the same configuration. The spectrum was wavelength calibrated using a third-order polynomial fit to observations of a Krypton-Mercury lamp, and the calibration checked against the Balmer line positions in the white dwarf.

Fig. 2.— (Following page) (a)—The spectrum (flux per unit frequency in arbitrary units) of Q1937−1009 extracted from the two-dimensional spectral image of Figure 1 is shown as a function of the rest wavelength in the $z = 3.572$ quasar absorption line frame, showing the position of the Lyman continuum break. The solid line shows a fit to the upper envelope of the spectrum redward of the Lyα emission line, excluding known emission lines. The dash–dot line shows the level of the corresponding continuum expected blueward of the Lyα emission line from ref. 13 . The dotted line shows a simple linear fit to the upper envelope of the continuum just above the Lyman continuum break. The dashed line shows the expected residual flux from the prediction of ref. 6. The error bar shows the uncertainty in that prediction, including both the quoted statistical and systematic errors. Both this spectrum and the higher resolution spectrum (below) were oversampled and are plotted without smoothing. (b)— The higher resolution spectrum ($R \sim 1500$) is shown as flux per unit frequency as a function of rest wavelength in the quasar absorption line frame. The spectrum was extracted in the same way as the lower resolution spectrum was, and its spectrophotometry found to be in good agreement with the lower resolution wide-slit spectrum. This higher resolution shows the rich forest of Lyman alpha lines. We show again both the linear (dotted) and ref. 13 (dash–dot) continuum fits. We have measured the optical depth at 890 Å in the rest frame, where the signal-to-noise is still high in the residual spectrum, and find an optical depth, $\tau = 2.4$ for the continuum of ref. 13 and $\tau = 3.1$ for the linear fit.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2.5
2
1.5
1
0.5
0
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−1
800
900
1000
1100
1200
1300
1400
1500
b
FLUX
WAVELENGTH (A)
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400
300
200
100
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850
900
950
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